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Spectral Irradiance Calibration in the Infrared. VIII. 5–14 μm Spectroscopy of the Asteroids Ceres, Vesta, and Pallas

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Abstract

We describe our efforts to seek "closure" in our infrared absolute calibration scheme by comparing spectra of asteroids, absolutely calibrated through reference stars, with "Standard Thermal Models" and "Thermophysical Models" for these bodies. Our use of continuous 5–14 μm airborne spectra provides complete sampling of the rise to, and peak, of the infrared spectral energy distribution and constrains these models. Such models currently support the absolute calibration of ISO-PHOT at far-infrared wavelengths (as far as 300 μm), and contribute to that of the Mid-Infrared Spectrometer on the "Infrared Telescope in Space" in the 6–12 μm region. The best match to our observed spectra of Ceres and Vesta is a standard thermal model using a beaming factor of unity. We also report the presence of three emissivity features in Ceres which may complicate the traditional model extrapolation to the far-infrared from contemporaneous ground-based N-band photometry that is used to support calibration of, for example, ISO-PHOT. While identification of specific materials that cause these features is not made, we discuss families of minerals that may be responsible.

cludes these emission features.

2. The observations

Table 1 summarizes the KAO HIFOGS spectra we have obtained of Ceres, Vesta, and Pallas since 1992. On any flight we took overlapping spectra displaced by a half integral number of detector elements to achieve the full instrumental resolution and to cover dead detectors. Thus a "5–14 μm" spectrum actually consists of at least four such spectra which we have overlapped by the splicing technique described in Paper II. Consequently, four distinct components of error enter into the ratio of an asteroid spectrum to that of our stellar calibrator. First, there are the individual photometric uncertainties from the statistics of all measurements of the asteroid by a single detector element in HIFOGS' arrays. Second are the corresponding errors in the spectra of the stellar standard. Third are the local "biases" (see Papers II,IV) that arise whenever two spectral fragments are spliced and overlapped. Finally there are uncertainties in the adopted absolute calibration of the stellar standard (which are derived from the same considerations applied to the secondary standard and to our KAO data of Sirius or Vega). We combine all these components in a root-sum-square sense into the total absolute uncertainty of the asteroid's spectrum. As in previous work, we remove any residual terrestrial atmospheric effects due to the imperfectly matched airmasses of asteroid and stellar spectra using Lord's (1992) ATRAN software. The pedigree of the two stellar calibrators used in this study of asteroids is documented in Paper II (α Tau) and Paper VII (α Boo).

In addition to these airborne data, we took a series of HIFOGS spectra of Vesta from the Mt Lemmon Observatory (hereafter MLO) in February 1992 that provide much more rigorous tests of model energy distributions. These are also summarized in Table 1.

3. Comparison of models and observations

a) Thermal and thermophysical models

The STM is a very simple model that treats asteroids as non-rotating spherical bodies with a smooth surface, observed at zero phase angle. Its lineage (L. A. Lebofsky 1997, private communication) is that of a model originally applied strictly to broadband 10-μm photometry, in which the true temperature distribution of an asteroid is not known, but assumed. Allowance for non-zero phase angles depends on an adopted phase coefficient whose typical value (0.01 mag deg^{-1}), in combination with that for the "beaming" parameter (allowance for preferential directing of radiation toward the Sun), is adjusted to match the absolute N-band flux level and occultation diameters of specific asteroids. Its application to wavelengths both shorter and longer than the broad 10-μm N-band has been problematic (e.g. Lebofsky 1989). The mere existence of beaming implies an excess of radiation is emitted in the zero phase direction and consequently less at larger phase angles, to conserve energy. Further, it is known (Lebofsky et al. 1984) that the prograde rotation of Ceres leads to different phase coefficients before and after opposition, although the average coefficient is preserved. Thus spectra taken after opposition (phase >22°), sample lower temperatures than those predicted by the STM, even allowing for phase correction. This morning/evening effect alone results in a systematic variation of order 10% in flux received from Ceres. These problems all highlight the importance of thermal inertia whose neglect, in the STM, renders subsolar point on Ceres was essentially constant and the shape of the single model from April 14 (the closest geocentrically) can be used to represent our expectation of Ceres during this flight series. This conclusion is also supported by the absence of spatial variations ($\leq 5\%$) across the surface of Ceres in the images observed at 2.2 and 3.8 μm, with adaptive optics, by Saint-Pe et al. (1993).

We have tested this conclusion in two ways. First, we compared the shapes of overlapping spectral fragments from different flights in the 1995 series, and from the "half-integral bin-shifted" fragments within each flight. We see no statistically significant distinctions between these fragments, above the $\pm 1\sigma$ level. Next we ratioed the three STMs for April 14, 19, and May 5 and found that these have identical shapes, and identical levels if one simply multiplies these by 1, 1.06, and 1.26, respectively. These factors are roughly what one expects from the varying geocentric distance of Ceres, coupled with its essentially constant heliocentric distance.

Our methodology for spectral assembly applied to stars depends on the use of independent photometry through well-characterized passbands so that one can normalize (some) spectral fragment(s) to the observed in-band fluxes. For Ceres, however, we have been unable to locate any such photometry during the spring of 1995 that is contained within the 5–14 μm region. We doubt that our KAO spectral levels could be inaccurate by more than about 10–15%. Indeed, there is good support (at the $\sim$10% level) for the absolute calibration of the Ceres spectrum in Fig. 1 through the continuity of the flux calibration of the IRTS-MIRS on the basis of Ceres and of stars (cf. Tanabe et al. 1997). But, because we cannot quantify our accuracy by contemporary independent photometry, in subsequent discussions we emphasize the *shape* of the energy distributions predicted by the STMs, renormalizing these to facilitate comparison with our observed spectra.

Fig. 1 compares the observed spectrum (the mean$\pm 2\sigma$) with Osip's STM. The shape is rather poorly represented by such a model, particularly below 8 μm (as expected because of the effects of thermal inertia). The STM was originally cast in terms of the brightness temperature and was intended to be normalized to the broadband 10 μm flux of an asteroid (L. A. Lebofsky 1997, private communication). The beaming parameter was adjusted, as needed, to match the broad N-band modeled and observed fluxes at zero phase to known occultation diameter. But this very broadband approach means that one does not know the real temperature distribution of the surface. With our higher spectral resolution we are sensitive to color temperature and this simply does not agree with the N-band brightness temperature. Many other factors enter into thermal models for asteroids, not the least of which is the phase correction. Our 1993 Ceres observations were taken at a phase angle of 8°; those from 1995 were made after opposition at phase angles > 22°. Ceres is a prograde rotator so that we observed its morning side in 1995. In such circumstances, the actual phase coefficient would be quite different from the adopted mean value of 0.01 mag deg^{-1}, and the temperature significantly lower than that predicted by the canonical STM. Even a photometric renormalization of the STM would not then match an observed spectrum, and the discrepancies would grow with distance from the wavelength of the thermal flux peak.

The value of η (the beaming parameter) is also controversial (cf. Morrison 1973). We note that Green et al. (1985) successfully modeled their MIR spectra of 12 main belt asteroids using the STM with η=0.9. There is even precedent for the use of η=1 (cf. Paper II, for Juno). Both these previous applications of the STM were to MIR spectroscopy.

Merrill (1975) and by Green et al. (1985). These authors adopted blackbody continua for their standard stars, which introduces spurious structure in the 10 μm region due to the neglect of the SiO fundamental in their reference stars (of order 15% in α Tau and 8% in α Boo at their resolutions). The primary SiO structure in their two calibration stars is in the 7.9–8.5 μm range yet the Ceres spectrum by Gillett & Merrill shows an emission feature remarkably similar to our own in the 9–11 μm. If this were not attributable to problems with telluric ozone cancellation then these data also would support the existence of a broad emission feature in this asteroid. Likewise, correction of the Ceres spectra of Green et al., for neglect of the SiO fundamental in α Boo, leads to the conclusion that they too saw a weak emission feature rising above the continuum beyond 8.5 μm.

To facilitate direct comparison with laboratory spectra, we also divided each set of scaled observations by the relevant STM continuum to create an emittance spectrum for Ceres. Specifically, we normalized the wavelength regions where the emittance approaches unity to the *high* points in both the 1993 and 1995 calibrated spectra of Ceres. The two emittances were combined with inverse-variance weighting to produce the curve in Fig. 5. Error bars associated with the combined emittance spectrum are also shown.

5. Identifications of materials and Christiansen frequencies

In the MIR, mineralogical information is related to the wavelength (frequency) position of the observed emittance maximum, which defines the Christiansen frequency (CF: Salisbury 1993; Kahle, Palluconi, & Christensen 1993). The CF is defined as the frequency where the real index of the sample (n_s) equals the index of the surrounding medium (n_m, i.e., vacuum or air). It has been demonstrated recently that the emissivity maximum does not occur at the exact wavelength where $n_s = n_m$ (Hapke 1996). Here we use the term "CF" to refer to the position of the emittance maximum. For silicate minerals the CF has been related to the degree or extent of polymerization of the SiO_4 tetrahedra. Highly polymerized silicates (e.g., quartz, feldspars) have CFs that occur at shorter wavelengths than those of silicates with lower degree pf polymerization (e.g., olivines: Salisbury 1993; Kahle et al. 1993). Systematic characterization of the CF behavior of non-silicates (e.g., oxides, metals, ices, organics) has not been discussed in the literature. For the MIR data of Ceres, we associate the maximum near 9.5 μm with the CF.

For solid particulate surfaces, the spectral contrast of MIR restrahlen features is inversely correlated with particle size and porosity (Salisbury 1993). There is no direct information regarding the particle size distribution of the materials on Ceres' surface. The lunar regolith, directly sampled during the Apollo missions, has a median particle diameter of 40–130 μm, with an average particle diameter of 70 μm (Carrier 1973). Here we *assume* a similar particle size distribution exists on Ceres.

The polarimetric signature for small asteroids is consistent with a coarse regolith depleted in the smallest particles (Dollfus et al. 1989). This depletion is attributed to low surface gravity. Polarimetry of Vesta (diameter 550 km) indicates some depletion of small particles, but particles bigger than 50 μm appear to be coated with particles smaller than 10 μm (Le Bertre & Zellner 1980). Ceres (diameter 934 km) could be assumed to have retained even more fine particles, thus resembling the Moon more than small asteroids in this respect. Furthermore, the nature of the small particles may be different since the polarization studies sample only optical radiation. In the MIR, the polarized light may result primarily from ment could perhaps be mitigated by a finer grain size or mixing of the tholin with a higher emissivity material, but such measurements are not available, and theoretical calculations of such mixtures are beyond the scope of this paper. Ceres is a C-type asteroid which is commonly associated with carbonaceous chondrite meteorites. Also shown in Fig. 6 is the calculated emissivity of the bulk powder of the Murchison meteorite. The spectral contrast exhibited by Murchison's emissivity spectrum is very low compared to the Ceres data. The CF in the 9–9.2 μm region is close to, but not at, the position of the CF in the Ceres data.

The comparison of laboratory data with the Ceres observations remains the greatest shortcoming here, as in Lebofsky et al. (1981), and King et al. (1992). Lebofsky et al. measured pure materials without any indication of their grain sizes but at a temperature appropriate for Ceres. King et al. measured a single mixture with no indication of grain sizes of the components and at room temperature. Here we have used laboratory data from the literature; no mixtures of appropriate materials are available, much less at the appropriate temperatures. The problem with the Murchison data is that the obvious mechanism to increase the spectral contrast, by increasing the grain size, is in seeming conflict with the inferred presence of abundant fine-grained materials on like-sized bodies, e.g. Vesta.

Consequently, we cannot provide an exact spectral match to the Ceres data. Phyllosilicates exhibit CF that, for the available spectra, occur at too short a wavelength to be consistent with the Ceres spectrum. Organic materials do exhibit spectral features that are consistent with those seen in Ceres, although none of the available spectra provides a convincing comparison to the Ceres data. We note that organic materials exhibit a wide range of compositional variation and we have compared only with a few examples.

6. The absolute calibration of ISO and the IRTS

The major focus of this paper is on the consequences of the spectral structure in Ceres for calibration based on the STM. Therefore, we address the pragmatic issues of how to use Ceres for MIR calibration of the IRTS-MIRS in April 1995 and for FIR calibration of ISO-PHOT during the lifetime of ISO. The features we have found in Ceres' spectrum appear to be real, and reproduce on both long and short time scales so they should not be neglected. There is some evidence in our 1993 and 1995 observations for variation in the relative strengths of the 6.6 and 10 μm features, but their influence on the observed spectral energy distribution is always local, and at the 10% level at most.

a) The MIRS

We believe that any MIRS calibration using Ceres should be accomplished in two steps. The zero order expectation is a continuum spectrum based on the STM with η=1. First order modifications to this STM should then be made by the addition of three discrete emission features in accord with Fig. 4. This procedure should work for other detectors observing in the 6–14 μm regime too. We are well aware that our usage of the STM in this fashion is an oversimplification of the real situation yet, empirically, it seems to replicate the observed thermal continua in Ceres (and Vesta) better than either the canonical STM or a TPM. Perhaps the neglect of thermal inertia in the STM is mitigated because of the large phase angles in the 1995 flight series on Ceres (L. A. Lebofsky 1997, private communication).

b) ISO-PHOT

We are grateful to NASA's Airborne Astronomy program and to the staff of the entire KAO program for their past support of these flights. MC also acknowledges the support at VRI of the University of Florida through a subcontract of NASA Grant NAG 5-3343. We thank David Osip for providing us with the University of Florida STMs for all three asteroids, and Kin-Wing Chan for providing algorithms for computing the η=1 STMs of Ceres and for drawing our attention to the quality of fit between these models and our KAO spectra. The referee, Larry Lebofsky, provided valuable comments and substantive follow-up discussions. We are also grateful to Thomas Mueller for communicating to us the results of his computations of TPMs for Ceres. Ann Sprague was the P.I. of the February 1992 HIFOGS observations of Vesta that were taken by her and by two of the authors of the current paper.

References

Arnold, G. & C. Wagner 1988, Earth, Moon and Planets, 41, 161

Carrier, W.D.,III, 1973, The Moon, 6, 250

Christensen, P.R. & Harrison, S.T. 1993, JGR, 98, 19, 819

Cohen, M. & Davies, J. K. 1995, MNRAS, 276, 715 [Paper V]

Cohen, M., Walker, R. G., Barlow, M. J., & Deacon, J. R. 1992a, AJ, 104, 16 [Paper I]

Cohen, M., Walker, R. G., & Witteborn, F. C. 1992b, AJ, 104, 2030 [Paper II]

Cohen, M., Witteborn, F. C., Bregman, J.D., Wooden, D.H., Salama, A., & Metcalfe, L. 1996a, AJ, 112, 240 [Paper VI]

Cohen, M., Witteborn, F. C., Carbon, D. F., Augason, G. C., Wooden, D.H., Bregman, J.D., & Goorvitch, D. 1992c, AJ, 104, 2045 [Paper III]

Cohen, M., Witteborn, F. C., Walker, R. G., Bregman, J.D., & Wooden, D.H. 1995, AJ, 110, 275 [Paper IV]

Cohen, M., Witteborn, F. C., Carbon, D. F., Davies, J. K., Wooden, D.H. & Bregman, J.D. 1996b, AJ, 112, 2274 [Paper VII]

Conel, J.E. 1969, JGR, 74, 1614

Dollfus, A., Wolff, M., Gaeke, J. E., Lupishko, D. F. & Dougherty, L. M. 1989,in "Asteroids II", 594 (eds. R. P. Binzel, T. Gehrels & M. S. Matthews)

Feierberg, M. A., Witteborn, Fred C. & Lebofsky, L. A. 1983,Icarus, 56,393

Gaffey, M.J., Bell, J.F., & Cruikshank, D.P. 1989, in "Asteroids II", (eds. R.P. Binzel, T. Gehrels, & M.S. Matthews), 98, (Univ. of Arizona Press)

Green, S. F., Eaton, N., Aitken, D. K., Roche, P. F. & Meadows, AJ,1985,Icarus, 62, 282

Gillett, F. C. & Merrill, K. M. 1975, Icarus 26, 358

Hansen, O. L. 1976, Icarus, 27, 453

Hapke, B. 1996, JGR, 101, 16833

Henderson, B.G. & Jakosky, B.M. 1997, JGR, 102, 6567

Henderson, B.G., Lucey, P.G. & Jakosky, B.M. 1996, JGR, 101, 14,969

Jones, T.J. & Morrison, D. 1974, AJ, 79, 892

Kahle, A.B., Palluconi, F.D., & Christensen, P.R. 1993, in Remote Geochemical Analysis: Elemental and Mineralogical Composition, eds. C.M. Pieters & P.A.J. Englert (Cambridge University Press), pg.99

Kessler, M.F. et al. 1997, A&A, 315, L27

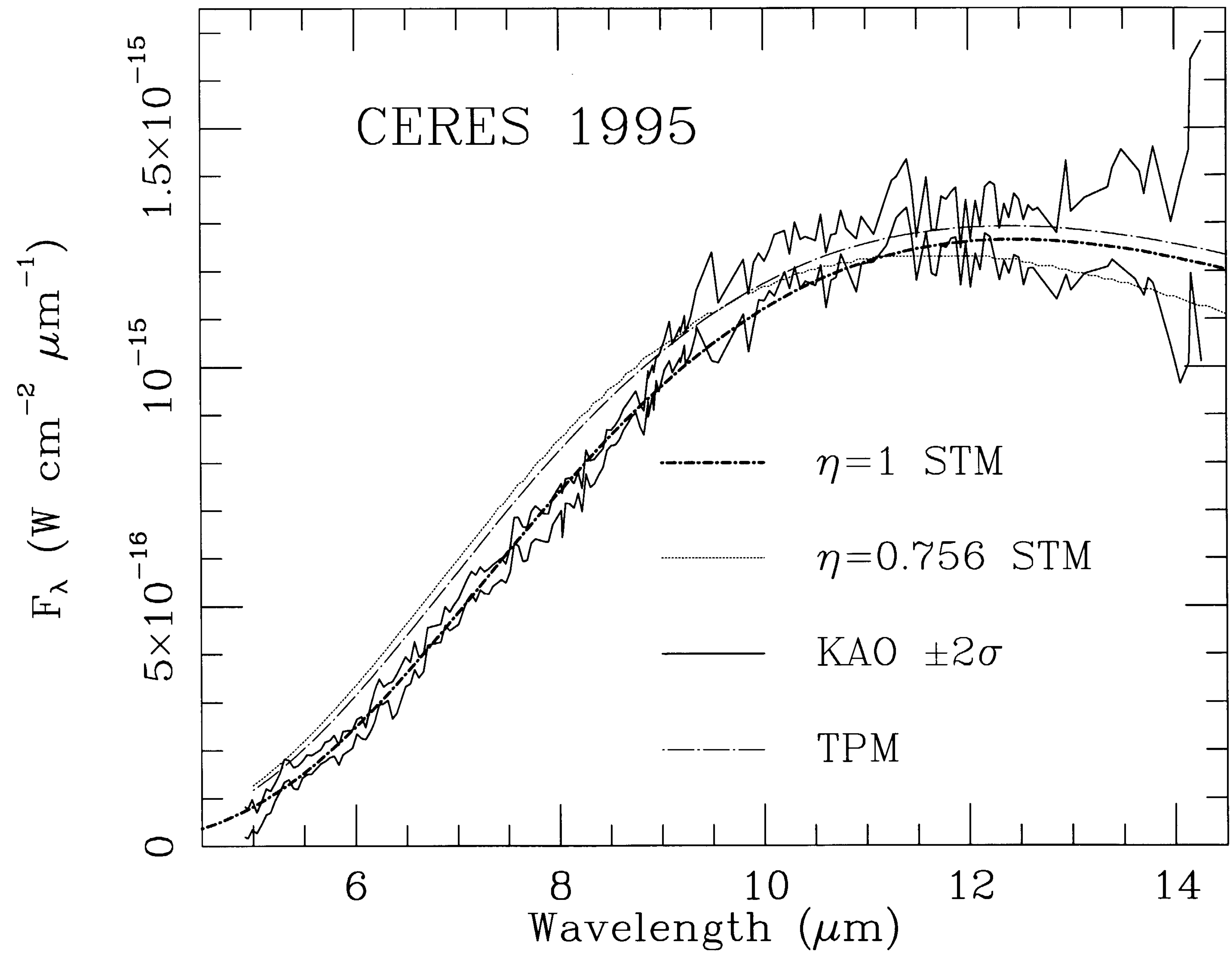
King, T.V.V., Clark, R.N., Calvin, W.M., Sherman, D.M. & Brown, R.H. 1992, Science, 255, 1551

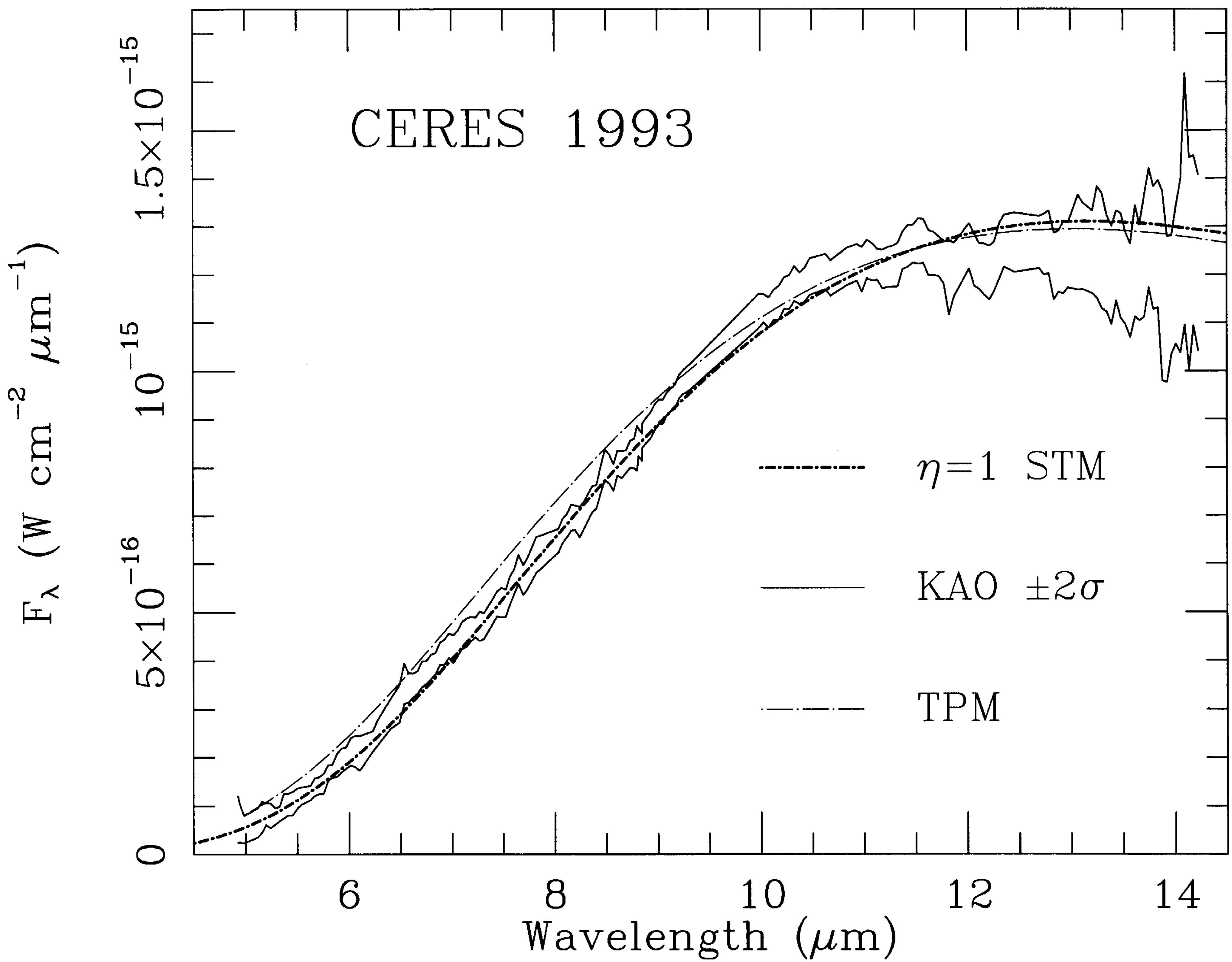
Lagerros, J.S.V. 1996, A&A, 310, 1011

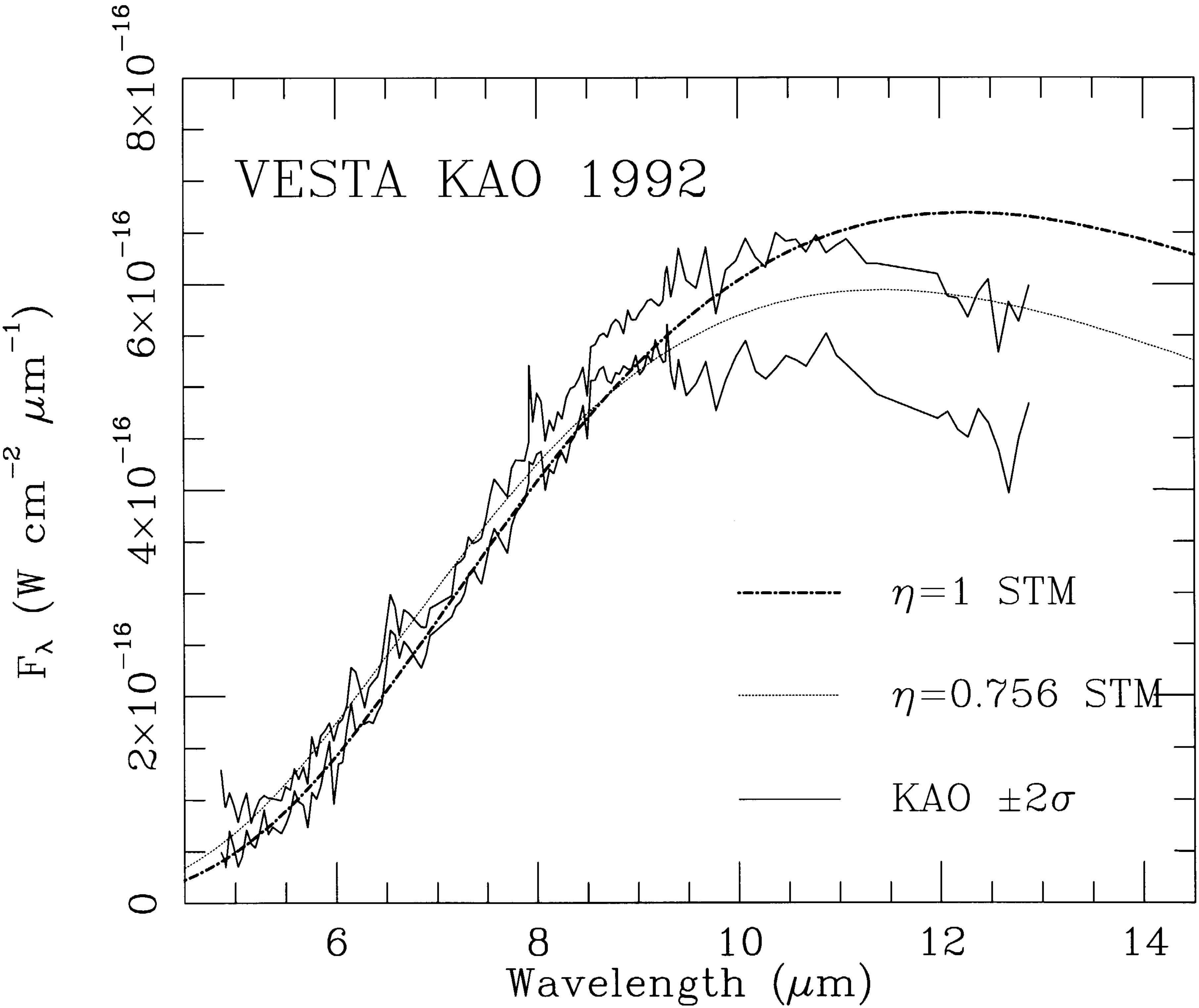
Lagerros, J.S.V. 1997, A&A, 325, 1226

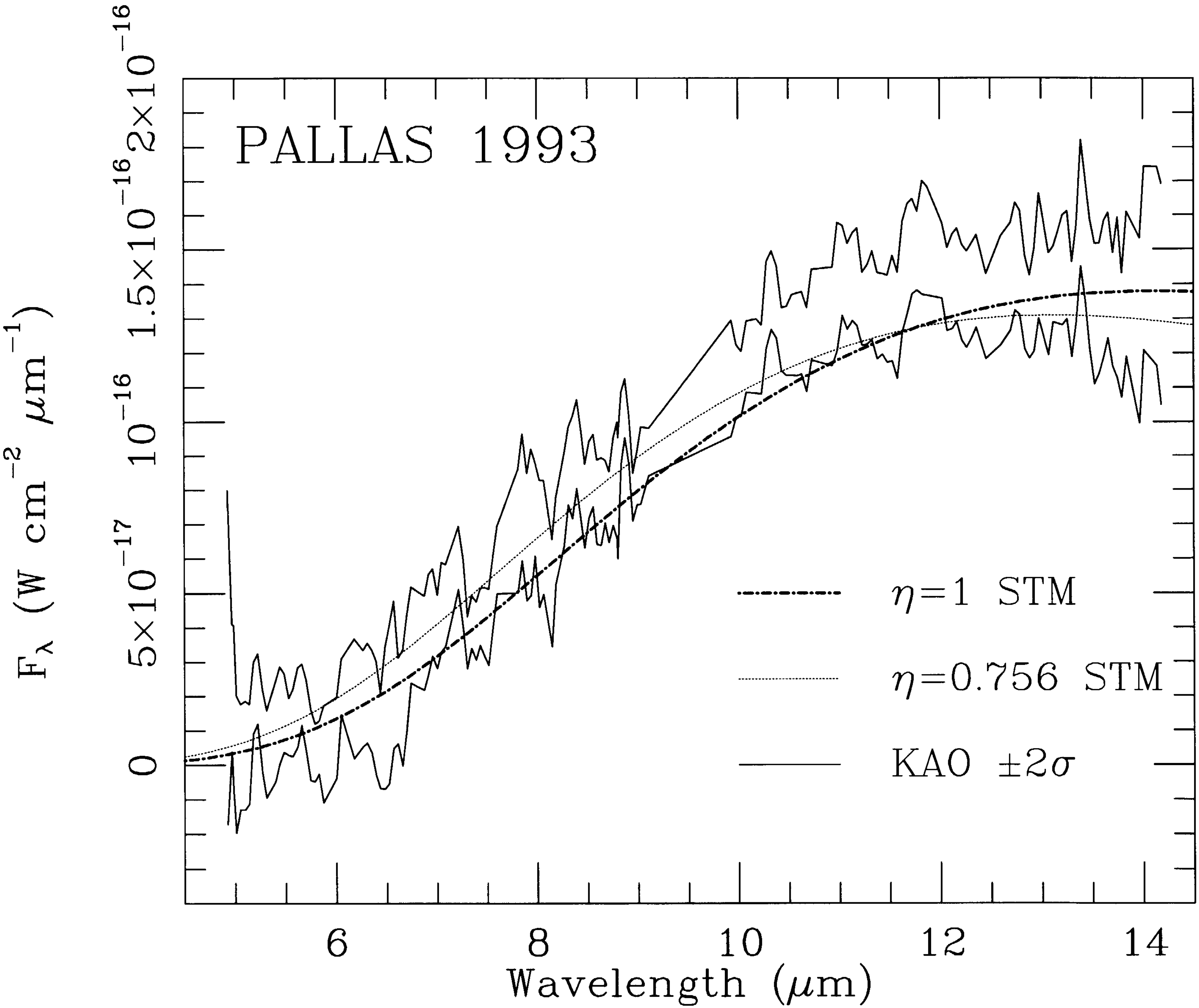
Table 1. Journal of 5–14 μm HIFOGS asteroid spectra from KAO or MLO.

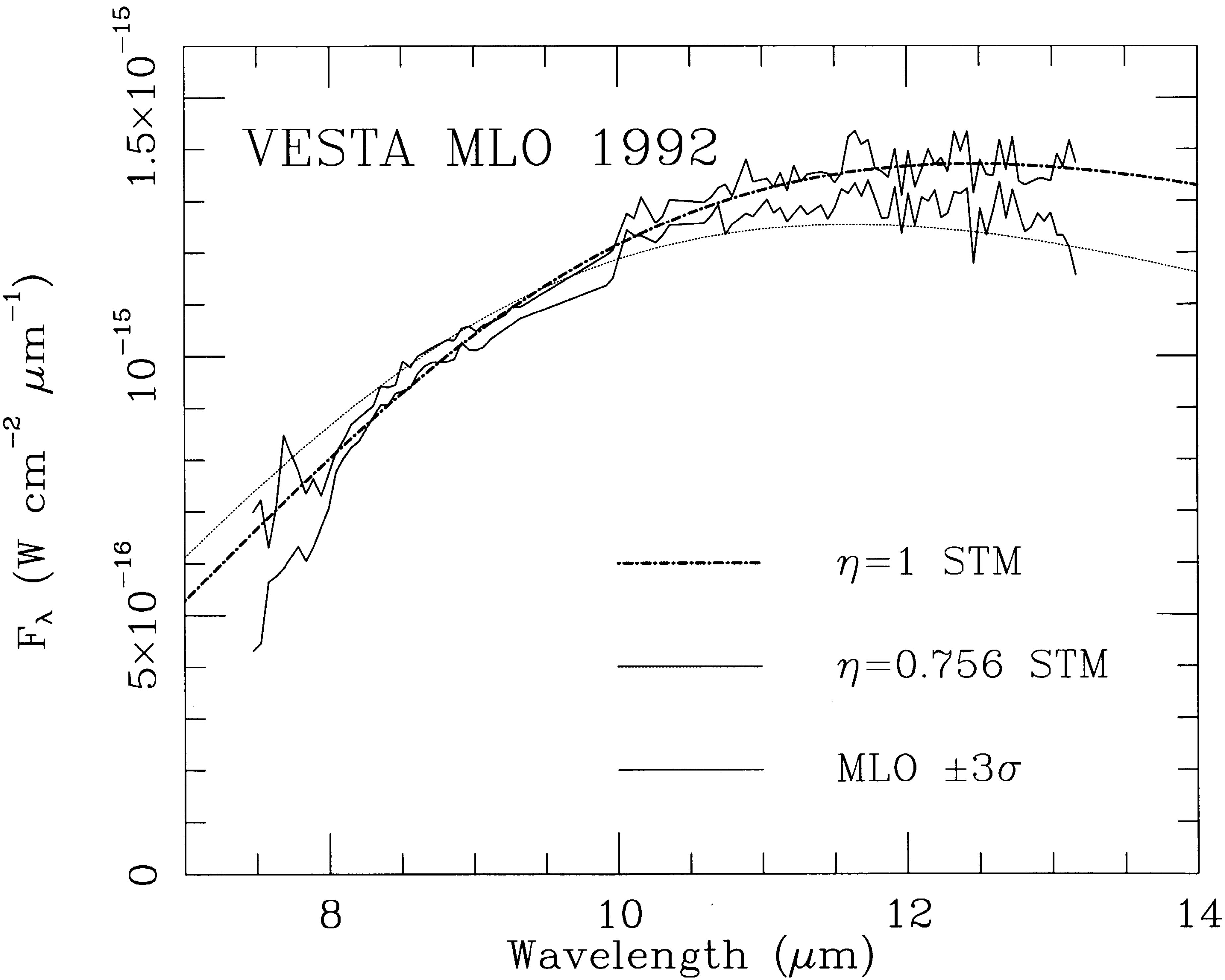
Date	Site	UT range	Phase angle (°)	Asteroid	Calibrator	Wavelengths (μm)	Resolving power
1992 Feb. 24	MLO	8.30–8.50	8.2	Vesta	α Boo	7.47–13.16	200
		10.50–11.10			α Boo	7.47–13.16	200
		11.51–12.11			α Boo	7.47–13.16	200
1992 May 12	KAO	5.27–6.44	25.1	Vesta	α Boo	4.86–9.28	150
					α Boo	4.90–9.41	150
					α Boo	7.83–14.18	110
1993 Nov. 9	KAO	2.25-4.05	17.7	Pallas	α Tau	4.88–9.37	170
					α Tau	4.94–9.44	170
					α Tau	8.80–14.22	230
					α Tau	9.08–14.27	230
1993 Nov. 9	KAO	4.22-5.54	8.0	Ceres	α Tau	4.88–9.37	170
					α Tau	4.94–9.44	170
					α Tau	8.80–14.22	230
					α Tau	9.08–14.27	230
1995 Apr. 14	KAO	5.09–5.30	22.3	Ceres	α Boo	4.92–9.37	170
					α Boo	4.94–9.40	170
1995 Apr. 19	KAO	4.45–5.20	22.7	Ceres	α Boo	4.92–9.37	170
					α Boo	4.94–9.40	170
1995 May 5	KAO	3.35–4.25	23.2	Ceres	α Boo	4.92–9.37	170
					α Boo	4.94–9.40	170
					α Boo	8.03–13.75	230
					α Boo	8.41–14.14	230

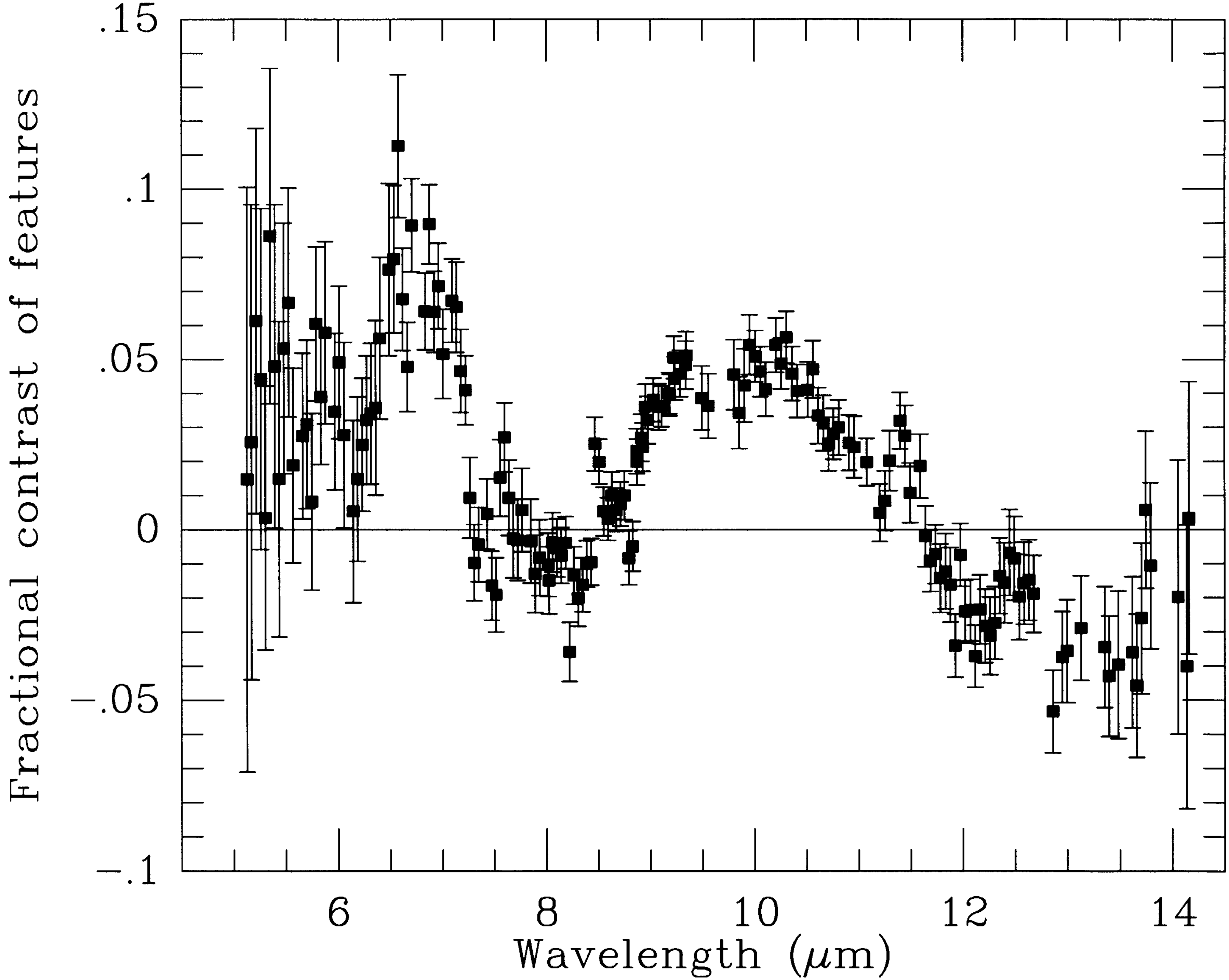

CERES 1995
η=1 STM
η=0.756 STM
KAO ±2σ
TPM
Wavelength (μm)
F$_\lambda$ (W cm^{-2} μm^{-1})
0
5×10^{-16}
10^{-15}
1.5×10^{-15}
6
8
10
12
14


CERES 1993
η=1 STM
KAO ±2σ
TPM
Wavelength (μm)
F_λ (W cm^-2 μm^-1)
0
5×10^-16
10^-15
1.5×10^-15
6
8
10
12
14

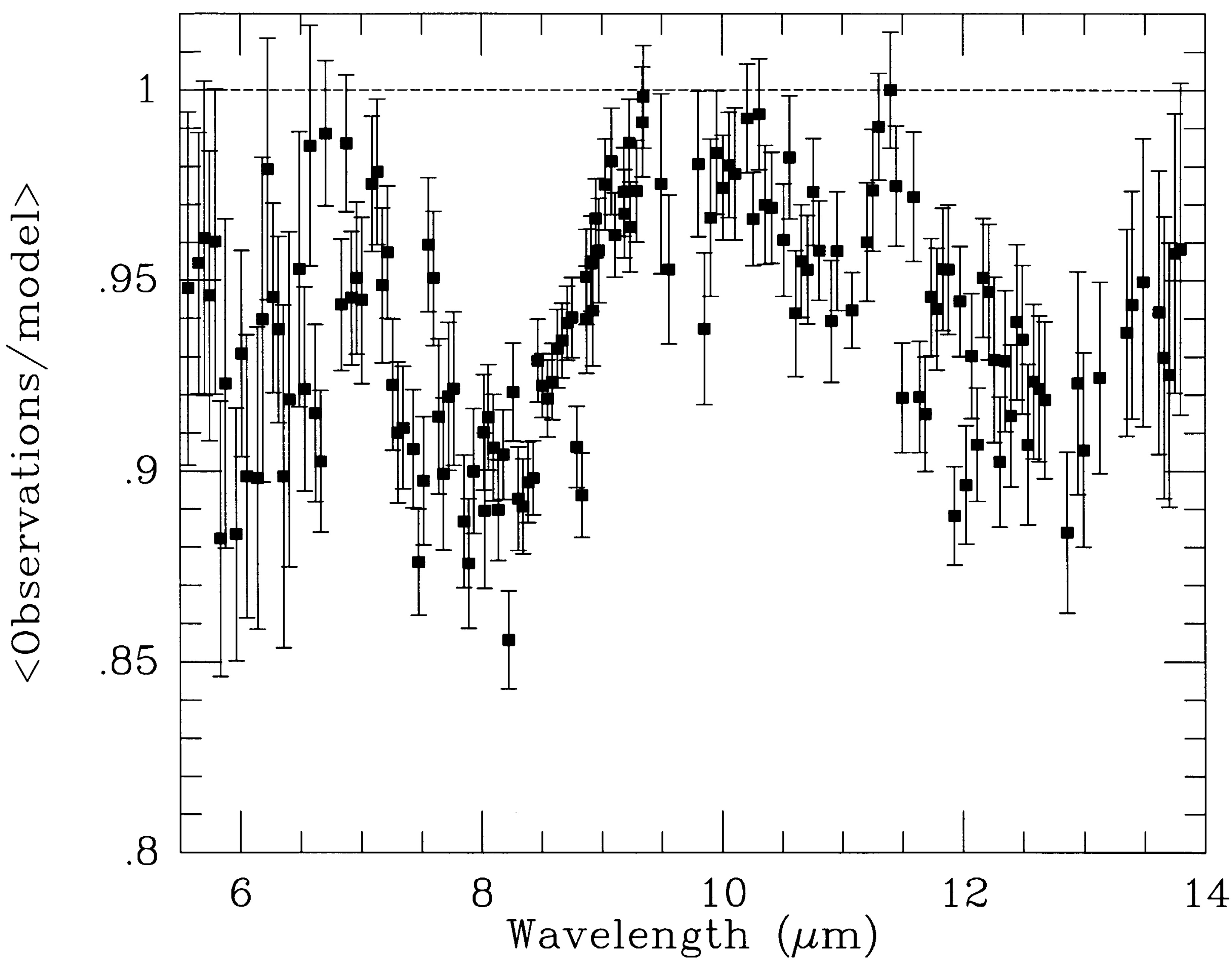

VESTA KAO 1992
η=1 STM
η=0.756 STM
KAO $\pm 2\sigma$
F_λ (W cm^{-2} μm^{-1})
0
2×10^{-16}
4×10^{-16}
6×10^{-16}
8×10^{-16}
6
8
10
12
14
Wavelength (μm)


PALLAS 1993
η=1 STM
η=0.756 STM
KAO ±2σ
Wavelength (μm)
F_λ (W cm^-2 μm^-1)
0
5×10^-17
10^-16
1.5×10^-16
2×10^-16
6
8
10
12
14


VESTA MLO 1992
F_λ (W cm^{-2} μm^{-1})
1.5×10^{-15}
10^{-15}
5×10^{-16}
0
8
10
12
14
Wavelength (μm)
η=1 STM
η=0.756 STM
MLO $\pm3\sigma$



.15
.1
.05
0
−.05
−.1
6
8
10
12
14
Wavelength (μm)
Fractional contrast of features



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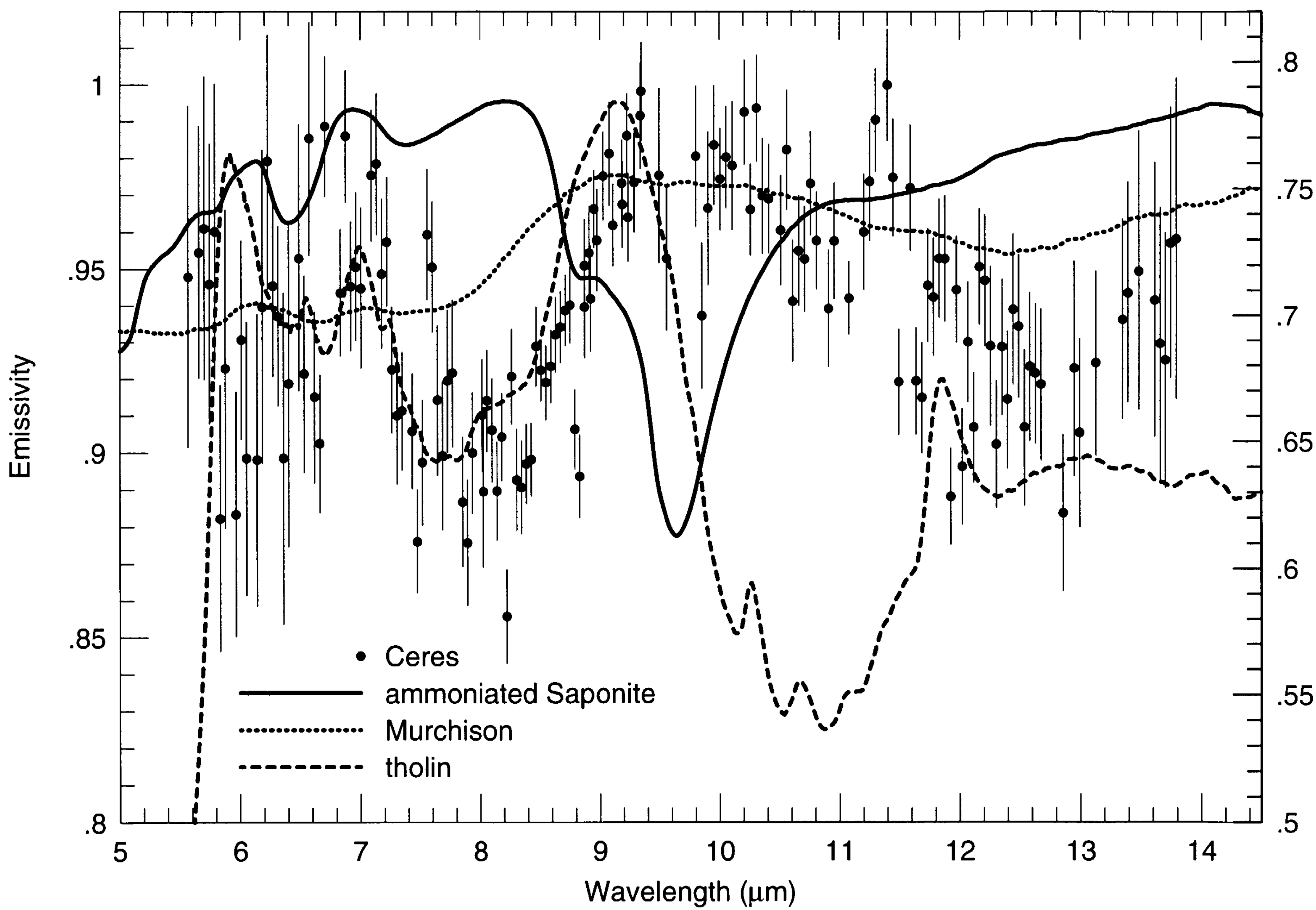
1
.95
.9
.85
.8
6
8
10
12
14
Wavelength (μm)



Emissivity
1
.95
.9
.85
.8
.8
.75
.7
.65
.6
.55
.5
5
6
7
8
9
10
11
12
13
14
Wavelength (µm)
Ceres
ammoniated Saponite
Murchison
tholin

TECHNICAL REPORT FOR NCC 2-142

Co-operative agreement with UC Berkeley

P.I. Martin Cohen

This technical report is a substitute for the Semi-Annual Status Report

Period covered: July 1 - December 31, 1997

ACTIVITIES

This 6 month period continued the effort on absolute spectrally continuous stellar calibration begun in January 1991.

The MSX DCATT team has continued its analysis and intercomparisons of the SPIRIT-III ground calibration, the on-orbit stellar calibration (using our stellar spectra), and the on-orbit observations of the MIT Lincoln Labs. "emissive spheres". All three approaches are in very good agreement, at about the +/-3% level (absolute). This demonstrates the consistency of our overall calibration scheme and validates the context in which ISO and MSX data also reside.

The work in support of the IRTS continues. The ISAS teams recently remeasured the wavelength profiles of the NIRS spectrometer; the MIRS will be next to be recharacterized. I plan to calibrate all these profiles as soon as I receive them. The primary new ingredient is represented by the acceptance for publication of the 8th paper in our calibration series that treats the spectrum of the asteroid Ceres and how, pragmatically, one should represent its energy distribution for usage by satellites. The most interested recipients of this information are the members of the MIRS team, who actually depend on Ceres for their longer wavelength absolute and relative calibration.

The liaison with the ISO Calibration Working Group continues very fruitfully. I attended both the CWG meeting in September 1997 and the special spectroscopy meeting in Madrid in October 1997, as ESA's designated US calibration advisor to ISO, and summarized our recent efforts on behalf of ISO, comparing with both DIRBE and MSX feedback on the common framework of stars.

Attached: preprint of Paper VIII, in press for The Astronomical Journal, May 1998 issue